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DIRECT AND INVERSE PROBLEMS IN STATISTICAL WAVEFIELDS

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Final Report

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DISCLAIMER

LIST OF CONTENTS

I. INTRODUCTION

In this report account is presented of research carried out during the period September 1, 1999 - August 31, 2002 under the sponsorship of the Department of Energy, grant DE-FG02-90ER 14119.

The research covered several areas of modern optical physics, particularly propagation of partially coherent light and its interaction with deterministic and with random media, spectroscopy with partially coherent light, polarization properties of statistical wave fields, effects of moving diffusers on coherence and on the spectra of light transmitted and scattered by them, reciprocity inequalities involving spatial and angular correlations of partially coherent beams, spreading of partially coherent beams in random media, inverse source problems, computed and diffraction tomography and partially coherent solitons. We have discovered a new phenomenon in an emerging field of physical optics, known as singular optics; specifically we found that the spectrum of light changes drastically in the neighborhood of points where the intensity has zero value and where, consequently, the phase becomes singular, We noted some potential applications of this phenomenon.

The results of our investigations were reported in 39 publications. They are listed on pages 3 to 5. Summaries of these publications are given on pages 6 - 13. Scientists who have participated in this research are listed on page 14.

II. LIST OF PUBLICATIONS RESULTING FROM RESEARCH SUPPORTED BY GRANT DE-FG02-90ER 14119 DURING THE PERIOD SEPTEMBER 1, 1999-AUGUST 31, 2002

1. G. Gbur, D. James and E. Wolf, "Energy Conservation Law for Randomly Fluctuating Electromagnetic Fields", *Phys. Rev. E.* **59**, 4594-4599 (1999).

2. P. S. Carney, E. Wolf and G. S. Agarwal, "Diffraction Tomography using Power Extinction Measurements", *J. Opt. Soc. Amer. A* **16**, 2643-2648 (1999).

3. E. Wolf, T. Shirai, G. Agarwal and L. Mandel, "Storage and Retrieval of Correlation Functions of Partially Coherent Fields", *Opt. Lett.* **24**, 367-369 (1999).

4. G. Gbur and E. Wolf, "Phase Conjugation with Random Fields and with Deterministic and Random Scatterers", *Opt. Lett.* **24**, 10-12 (1999).

5. G. Gbur and E. Wolf, "Determination of Density Correlation Functions From Scattering of Polychromatic Light", *Opt. Commun.* **168**, 39-45 (1999).

6. S. A. Ponomarenko and E. Wolf, "Coherence Properties of Light in Young's Interference Pattern Formed with Partially Coherent Light", *Opt. Commun.* **170**, 1-8 (1999).

7. P. S. Carney and G. Gbur, "Optimal Apodizations for Finite Apertures", *J. Opt. Soc. Am.* **16**, 1638-1640 (1999).

8. S. A. Ponomarenko and A. V. Shchegrov, "Spectral Changes of Light Produced by Scattering from Disordered Anisotropic Media", *Phys. Rev. E.* **60**, 3310-3313 (1999).

9. G. Gbur and K. Kim, "Quasi-Homogeneous Approximation for a Class of Three-dimensional Primary Sources", *Opt. Commun.* **163**, 20-23 (1999).

10. A. V. Shchegrov, D. Birkedal and J. Shah, "Monte Carlo Simulations of Ultrafast Resonant Rayleigh Scattering from Quantum Well Excitons: Beyond Ensemble Averaging", *Phys. Rev. Letts.* **83**, 1391-4 (1999).

11. A. T. Friberg, T. D. Visser and E. Wolf, "A Reciprocity Inequality for Gaussian Schell-model Beams and some of its Consequences", *Opt. Letts.* **25**, 366-368 (2000).

12. E. Wolf, "Coherence of Two Interfering Beams Modulated by a Uniformly Moving Diffuser", *J. Mod. Opt.* **47**, 1569-1573 (2000).

13. S. Ponomarenko and E. Wolf, "Light Beams with Minimum Phase-space Product", *Opt. Letts.* **25**, 663-665 (2000).

14. G. Gbur and D. F. V. James, "Unpolarized Sources that Generate Highly Polarized Fields Outside the Source", *J. Mod. Opt.* **47**, 1171-1177 (2000).

15. D. Birkedal, J. Shah, A. V. Shchegrov and L. N. Pfeiffer, "Experimental Investigation of Quantum Effects in the Time Resolved Resonance Rayleigh Scattering from Quantum Well Excitons", *Physica Status Solidi A* **178**, 5-11 (2000).

16. A. V. Shchegrov, J. Bloch, D. Birkedal and J. Shah, "Theory of Resonant Rayleigh Scattering from Semiconductor Microcavities: Signatures of Disorder", *Phys. Rev. Letts.* **84**, 3478-3481 (2000).

17. T. Shirai and E. Wolf, "Transformation of Coherence and of the Spectrum of Light by a Moving Diffuser", *J. Mod. Opt.* **182**, 265-272 (2000).

18. A. V. Shchegrov, K. Joulain, R. Carminati and J.-J. Greffet, "Near-field Spectral Due to Electromagnetic Surface Excitations", *Phys. Rev. Letts.* **85**, 1548-1551 (2000).

19. G. P. Agrawal and E. Wolf, "Propagation–induced Polarization Changes in Partially Coherent Optical Beams", *J. Opt. Soc. Amer. A* **17**, 2019-2023 (2000).

20. T. Visser, A. T. Friberg and E. Wolf, "Phase-space Inequality for Partially Coherent Beams", *Opt. Commun.* **187**, 1-6 (2001).

21. S. Ponomarenko and E. Wolf, "Effective Spatial and Angular Correlations in Beams of any State of Coherence and an Associated Phase-space Product", *Opt. Lett.* **26**, 122-124 (2001).

22. G. Gbur, "Uniqueness of the Solution to the Inverse Source Problem for Quasi-homogeneous Sources", *Opt. Commun.* **187**, 301-309 (2001).

23. S. Ponomarenko, "Class of Partially Coherent Beams Carrying Optical Vortices", submitted to *J. Opt. Soc. Amer.* A **18**, 150-156 (2001).

24. G. Gbur and E. Wolf, "Relation Between Computed Tomography (CAT) and Diffraction Tomography", *J. Opt. Soc. Amer.* A **18**, 2132-2137 (2001).

25. S. Ponomarenko and E. Wolf, "Correlations in Open Quantum Systems and Associated Uncertainty Relations", *Phys. Rev. A* **63**, 1-5 (2001).

26. G. Gbur and E. Wolf, "The Rayleigh Range of Gaussian Schell-model Beams", *J. Mod. Opt.* **48**, 1735-1741 (2001).

27. E. Wolf, "Modulation of Coherence and Some of its Applications", in *Proceedings of the Nineteenth Symposium on Energy Engineering Sciences*, Argonne National Laboratory, Argonne, IL, 2001.

28. A. T. Friberg, T. D. Visser, W. Wang and E. Wolf, "Focal Shifts of Converging Diffracted Waves of any State of Spatial Coherence", *Opt. Commun.* **196**, 1-7 (2001).

29. G. Gbur and E. Wolf, "The Rayleigh Range of Partially Coherent Beams", *Opt. Commun.* **199**, 295-304 (2001).

30. P. Scott Carney and E. Wolf, "Power-extinction Diffraction Tomography with Partially Coherent Light", *Opt. Lett.* **26**, 1770-1772 (2001).

31. S. Ponomarenko, "Twisted Gaussian Schell-model Solitons", *Phys. Rev. E* **64**, 036618, 1-5 (2001).

32. S. Ponomarenko, "Linear Superposition Principle for Partially Coherent Solitons", *Phys. Rev. E.* **65**, 055601, 1-4 (2002).

33. G. Gbur, T. D. Visser and E. Wolf, "Anomalous Behavior of Spectra near Phase Singularities of Focused Waves", *Phys. Rev. Lett.* **88**, 013901,1-4 (2002).

34. S. Ponomarenko and E. Wolf, "Universal Structure of Field Correlations within a Fluctuating Medium", *Phys. Rev. E.* **65**, 016602, 1-6 (2002).

35. T. Shirai and E. Wolf, "Spatial Coherence Properties of the Far Field of a Class of Partially Coherent Beams which have the same Directionality as a Fully Coherent Laser Beam", *Opt. Comm.* **204**, 25-31 (2002).

36. G. Gbur and E. Wolf, "The Spreading of Partially Coherent Beams in Random Media", *J. Opt. Soc. Amer. A* **19**, 1592-1598 (2002).

37. G. Gbur, T. D. Visser and E. Wolf, "Singular Behavior of the Spectrum in the Neighborhood of Focus", *J. Opt. Soc. Amer. A.* 19, 1694-1700 (2002).

38. S. A. Ponomarenko, J.-J. Greffet and E. Wolf, "The Diffusion of Partially Coherent Beams in Turbulent Media", *Opt. Commun.* **208**, 1-8 (2002).

39. S. A. Ponomarenko and E. Wolf, "Spectral Anomalies in a Fraunhofer Diffraction Pattern", *Opt. Lett.* **27**, 1211-1213 (2002).

III. LIST OF SUMMARIES OF PUBLICATIONS RESULTING FROM RESEARCH SUPPORTED BY GRANT DE-FG02-90ER 14119 DURING THE PERIOD SEPTEMBER 1, 1999-AUGUST 31, 2002

1. **G. Gbur, D. James and E. Wolf, "Energy Conservation Law for Randomly Fluctuating Electromagnetic Fields", *Phys. Rev. E.* 59, 4594-4599 (1999).**

   An energy conservation law is derived for electromagnetic fields generated by any random, statistically stationary, source distribution. It is shown to provide insight into the phenomenon of correlation-induced spectral changes. The results are illustrated by an example.

2. **P. S. Carney, E. Wolf and G. S. Agarwal, "Diffraction Tomography using Power Extinction Measurements", *JOSA A* 16, 2643-2648 (1999).**

   We propose a new method for determining structures of semi-transparent media from measurements of the extinguished power in scattering experiments. The method circumvents the problem of measuring the phase of the scattered field. We illustrate how this technique may be used to reconstruct both deterministic and random scatterers.

3. **E. Wolf, T. Shirai, G. Agarwal and L. Mandel, "Storage and Retrieval of Correlation Functions of Partially Coherent Fields", *Opt. Lett.* 24, 367-369 (1999).**

   A new method is described for determining the two-point equal-time coherence function (the mutual intensity) and the two-point equal-time intensity correlation function of partially coherent fields. The method is reminiscent of conventional holography but differs from it in several important respects.

4. **G. Gbur and E. Wolf, "Phase Conjugation with Random Fields and with Deterministic and Random Scatterers", *Opt. Lett.* 24, 10-12 (1999).**

   The theory of distortion correction by phase conjugation, developed since the discovery of this phenomenon many years ago, applies to situations when the field that is conjugated is monochromatic and the medium with which it interacts is deterministic. In this Letter a generalization of the theory is presented that applies to phase conjugation of partially coherent waves interacting with either deterministic or random weakly scattering nonabsorbing media.

5. **G. Gbur and E. Wolf, "Determination of Density Correlation Functions from Scattering of Polychromatic Light", *Opt. Commun.* 168, 39-45 (1999).**

   It is shown that for some many-particle systems with a high degree of symmetry, the density correlation function may be determined by measurements of the changes in the spectrum of polychromatic light scattered by the particles. The use of spectral measurements for such inverse problems may appreciably reduce the number of measurements required to uniquely determine the system structure.

6. **S. A. Ponomarenko and E. Wolf, "Coherence Properties of Light in Young's Interference Pattern Formed with Partially Coherent Light", *Opt. Commun.* 170, 1-8 (1999).**

   It has been shown not long ago that the spectrum of light in Young's interference pattern formed by partially coherent light differs, in general, from the spectrum of light incident on the pinholes; and, moreover, that the spectrum depends on the position of the point of observation. In this paper we extend the analysis by deriving expressions for the spectral degree of coherence and for the cross-spectral density of intensity fluctuations of the light at any pair of points in the interference pattern. We illustrate the general results by examples.

7. **P. S. Carney and G. Gbur, "Optimal Apodizations for Finite Apertures", *J. Opt. Soc. Am.* 16, 1638-1640 (1999).**

   A method is presented for determining the aperture apodization functions needed to optimize any given product of powers of the even-order moments of the beam intensity in the near and far zones. The results are a generalization of previous work [*Pure Appl. Opt.* 7, 1221 (1998)] that dealt only with the far-zone moments. These methods are applied to the problem of optimizing the so-called beam propagation factor, M_P^2.

8. **S. A. Ponomarenko and A. V. Shchegrov, "Spectral Changes of Light Produced by Scattering from Disordered Anisotropic Media", *Phys. Rev. E.* 60, 3310-3313 (1999).**

   We investigate theoretically changes in the spectrum of polychromatic light scattered by a disordered, birefringent medium. We derive an expression for the spectrum of scattered light for ordinary and extraordinary incident waves within the accuracy of the first Born approximation. Using this result, we analyze the changes in the spectrum of light due to the combined action of disorder and anisotropy in the scattering process.

9. **G. Gbur and K. Kim, "Quasi-Homogeneous Approximation for a Class of Three-dimensional Primary Sources", *Opt. Commun.* 163, 20-23 (1999).**

   We investigate the validity of the quasi-homogeneous approximation for three-dimensional primary Gaussian Schell-model sources. It is shown that the quasi-homogeneous approximation is not valid for such a source unless two conditions are satisfied, one of which depends upon the spatial characteristics of the source, and the other depends upon the wavelength of the radiation. The second of these conditions appears not to have been appreciated in previous work relating to the quasi-homogeneous approximation, and its significance to the foundations of radiometry is discussed.

10. **A. V. Shchegrov, D. Birkedal and J. Shah, "Monte Carlo Simulations of Ultrafast Resonant Rayleigh Scattering from Quantum Well Excitons: Beyond Ensemble Averaging", *Phys. Rev. Letts.* 83, 1391-1394 (1999).**

    We develop and experimentally verify novel Monte Carlo simulations of ultrafast resonant Rayleigh scattering from quantum well excitons. In contrast to existing theories, these simulations can study the dynamics and spectrum of resonant Rayleigh scattering from a single realization of disorder, and allow direct comparison to experimental data. We find excellent agreement between our experiments and simulations. Our studies demonstrate the high sensitivity of scattering dynamics to a particular realization of disorder, and provide new insights into the nature of spatial correlations of excitons.

11. **A. T. Friberg, T. D. Visser and E. Wolf, "A Reciprocity Inequality for Gaussian Schell-model Beams and Some of its Consequences", *Opt. Letts.* 25, 366-368 (2000).**

    A reciprocity inequality is derived, involving the effective size of a planar, secondary, Gaussian Schell-model source and the effective angular spread of the beam, which the source generates. It is shown to imply that a fully spatially coherent source of that class (which generates the lowest-order Hermite-Gaussian laser mode) has certain minimal properties.

12. **E. Wolf, "Coherence of Two Interfering Beams Modulated by a Uniformly Moving Diffuser", *J. Mod. Opt.* 47, 1171-1177 (2000).**

    Coherence properties are discussed of light, which emerges from two pinholes after it has passed through a moving diffuser. The results are used to show how the correlation function of the heights of the diffuser surface and the speed with which the diffuser is moving may be determined from simple interference experiments.

13. **S. Ponomarenko and E. Wolf, "Light Beams with Minimum Phase-space Product", *Opt. Letts.* 25, 663-665 (2000).**

    We derive a reciprocity inequality involving the product of the effective size of a statistically stationary, planar, secondary source of any state of coherence and of the angular spread of the far-zone intensity generated by the source. We show that of all possible such sources, the fully spatially coherent lowest-order Hermite-Gaussian laser mode has the smallest possible reciprocity product.

14. **G. Gbur and D. F. V. James, "Unpolarized Sources that Generate Highly Polarized fields outside the source", *J. Mod. Opt.* 47, 1171-1177 (2000).**

    It is demonstrated that an unpolarized primary electromagnetic source may, under special conditions, produce a field outside the source domain that is almost completely polarized in nearly all directions. This result demonstrates that the polarization statistics of a random electromagnetic field may differ significantly from the polarization statistics of the source distribution that generates it, and may in fact be quite different in different directions of observation. An example of such a source is given.

15. **D. Birkedal, J. Shah, A. V. Shchegrov and L. N. Pfeiffer, "Experimental Investigation of Quantum Effects in the Time Resolved Resonance Rayleigh Scattering from Quantum Well Excitons", *Physica Status Solidi A* 178, 5-11 (2000).**

    Resonant Rayleigh scattering from quantum well excitons is investigated using ultrafast spectral interferometry. We isolate the coherent Rayleigh scattering from incoherent luminescence in a single speckle. Averaging the resonant Rayleigh intensity over several speckles allows us to identify features in support of quantum corrections to the classical description of the underlying scattering process.

16. **A. V. Shchegrov, J. Bloch, D. Birkedal and J. Shah, "Theory of Resonant Rayleigh Sscattering from Semiconductor Microcavities: signatures of disorder", *Phys. Rev. Letts.* 84, 3478-3481 (2000).**

    We develop a self-consistent, microscopic theory of coherent resonant secondary emission from semi-conductor microcavities in the normal-mode-coupling regime. Our theory provides a quantitative description of the spectral, temporal, and angular properties of the disorder-induced emission component - resonant Rayleigh scattering - and offers an intuitive physical explanation of emission properties.

17. **T. Shirai and E. Wolf, "Transformation of Coherence and of the Spectrum of Light by a Moving Diffuser", *J. Mod. Opt.* 182, 265-272 (2000).**

    Effects of a diffuser on the spectral degree of coherence and on the spectrum of light produced by transmitting light through the diffuser are described. Both stationary and uniformly moving diffusers are considered and the analysis applies to dielectric as well as to absorbing diffusers. The results are illustrated by numerical examples.

18. **A. V. Shchegrov, K. Joulain, R. Carminati and J-J. Greffet, "Near-field Spectral Effects Due to Electromagnetic Surface Excitations", *Phys. Rev. Letts.* 85, 1548-1551 (2000).**

    We demonstrate theoretically that the spectra of electromagnetic emission of surface systems can display remarkable differences in the near and far zones. The spectral changes occur due to the loss of evanescent modes and are especially pronounced for systems which support surface waves.

19. **G. P. Agrawal and E. Wolf, "Propagation–induced Polarization Changes in Partially Coherent Optical Beams", *J. Opt. Soc. Amer. A* 17, 2019-2023 (2000).**

    Propagation of a partially coherent optical beam inside a linear, nondispersive, dielectric medium is studied, taking into account the vector nature of the electromagnetic field. Propagation-induced polarization changes are studied by using the Gaussian-Schell model for the cross-spectral-density tensor. The degree of polarization changes with propagation and also becomes nonuniform across the beam cross section. The extent of these changes depends on the coherence radius associated with the cross-correlation function. For optical beams with symmetric spectra, the bandwidth of the source spectra is found to play a relatively minor role.

20. **T. Visser, A. T. Friberg and E. Wolf, "Phase-space Inequality for Partially Coherent Beams", *Opt. Commun.* 187, 1-6 (2001).**

    A phase-space inequality is derived for beams of arbitrary state of spatial coherence. It applies to the product of a factor which expresses the effective coherence area of the source that generates the beam and the effective angular spread of the beam; and, by analogy with coherent beams, it may be regarded as a measure of the beam quality. It is shown to set the scale of a low-pass filter that acts on the object. The implications of these results for implementation of the method are discussed.

31. S. Ponomarenko, "Twisted Gaussian Schell-model Solitons", *Phys. Rev. E* 64, 036618, 1-5 (2001).

We show that a certain class of spatially partially coherent solitons, namely, twisted Gaussian Schell-model solitons, exists in a logarithmically saturable nonlinear medium with a noninstantaneous temporal response. Unlike previously reported Gaussian Schell-model solitons, those discussed here carry a position-dependent twist phase, which vanishes in the fully coherent limit. We demonstrate that the presence of the twist phase provides an opportunity for controlling the degree of spatial coherence of such solitons without affecting their intensity.

32. S. Ponomarenko, "Linear Superposition Principle for Partially Coherent Solitons", *Phys. Rev. E.* 65, 055601, 1-4 (2001).

The existence of a linear superposition principle is demonstrated for partially coherent solitons with identical intensity profiles that are supported by the same medium. Since such degenerate partially coherent solitons are generic for saturable as well as for Kerr-like nonlinear media, our results are relevant to any noninstantaneous nonlinear media. The proposed superposition principle suggests a physical interpretation of partially coherent solitons as generalized linear modes of their self-induced waveguides. The power of such a superposition principle is illustrated by identifying soliton structures with controllable coherence properties both in logarithmically saturable and in Kerr-like nonlinear media.

33. G. Gbur, T. D. Visser and E. Wolf, "Anomalous Behavior of Spectra near Phase Singularities of Focused Waves", *Phys. Rev. Lett.* 88, 013901, 1-4 (2002).

It is shown that remarkable spectral changes take place in the neighborhood of phase singularities near the focus of a converging, spatially fully coherent polychromatic wave diffracted at an aperture. In particular, when the spectrum of the wave in the aperture consists of a single line with a narrow Gaussian profile, the spectrum near a phase singularity (i.e., near points of zero intensity of some particular spectral component) changes drastically along a closed loop around the singularity. The spectrum is redshifted at some points, blueshifts at otheres, and is split into two lines elsewhere.

34. S. Ponomarenko and E. Wolf, "Universal Structure of Field Correlations within a Fluctuating Medium", *Phys. Rev. E.* 65, 016602, 1-6 (2002).

We study the structure of the second-order correlation function of scalar wavefields, which are generated by statistically stationary sources, fluctuating within a homogeneous dissipative medium. We derive a closed-form analytical expression for the spectral degree of coherence of the wavefield. If the dissipation in the medium is sufficiently small, and the source fluctuations are statistically isotropic, the degree of spatial coherence of the field produced by any such source is shown to be proportional to the imaginary part of the Green's function of the system, with a proportionality factor depending on the dimensionality of the field. The result holds for wavefields in both

IV. SCIENTIFIC COLLABORATORS

In addition to Professor Emil Wolf, the Principal Investigator for this grant, the following scientists have taken part in this research:

AGARWAL, G. S.	Director, Physical Research Laboratory, Ahmedabad, India Visiting Research Scientist.
AGRAWAL, G. P.	Professor at the Institute of Optics, University of Rochester, Rochester, NY.
CARNEY, P. S.	Assistant Professor, Department of Electrical and Computer Engineering, University of Illinois at Urbana-Champaign.
FRIBERG, A. T.	Professor at the Royal Institute of Technology, Stockholm, Sweden.
GBUR, G.	Formerly a Graduate Student, now a Post-doctoral Fellow at University of Rochester.
GREFFET, J.-J.	Professor at l'Ecole Centrale Paris, Paris, France.
JAMES, D. F. V.	Post-doctoral Research Associate, Los Alamos National Laboratory, Los Alamos, NM.
KIM, K.	Professor at Inha University, Inchon, South Korea.
MANDEL. L.	Formerly Lee DuBridge Professor of Physics and Optics, University of Rochester, Rochester, NY.
PONOMARENKO, S.	Formerly a Graduate Student, now a Post-doctoral Fellow at University of Rochester.
SHCHEGROV, A.	Formerly Post-doctoral Fellow, University of Rochester, now a Senior Optical Modeling Engineer at Novalux, Inc., Sunnyvale, CA.
SHIRAI, T.	Visiting Research Associate from Mechanical Engineering Laboratory, MITI, Tsukuba, Japan
VISSER, T.	Visiting Research Associate from Vrije Universiteit, Amsterdam, The Netherlands.
WANG, W.	Formerly a Post-doctoral Fellow, University of Rochester now a Scientist at Verdant Technologies, San Jose, CA.